Forests in European Union’s climate policy – A case study of the forest reference level projection in Finland

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Tiivistelmä/Referat – Abstract

We analyse the forest reference level (FRL) projection in Finland. FRLs are included in the European Unions' new land use, land-use change and forestry (LULUCF) regulation (EU 2018/841) that is part of the actions towards the Paris Agreement's climate mitigation targets. The regulation defines the accounting rules for carbon dioxide (CO_2) emissions within the sector. We build on the LULUCF regulation, the provided guidance documents on the FRL projection, national forestry accounting plans and the existing studies concerning the FRL projections. Business-as-usual reference levels were used for the Kyoto Protocol's second commitment period. The parties of the Kyoto Protocol had an incentive to report high harvest levels (Frieden et al. 2012). Thus, the reference levels overestimated the harvests by including in assumptions about future policies. Some of the assumptions did not materialize and this led to windfall carbon credits (Grassi et al. 2018, Krug 2018). Such overestimation has happened, for example, in Finland. In this thesis we analyse, whether the new forest reference levels are able to avoid problems that occurred during the Kyoto Protocol.

The LULUCF regulation is set for the compliance period (CP) of 2021-2030. The forest reference level is a baseline projection for the forest carbon sink, defined by the historical forest management practices of the reference period (2000-2009). Age-related dynamics of the forest can be taken into account but any anticipated policy changes need to be excluded from the projection. The FRL indirectly defines the level of harvests that are not considered as emissions. The excess carbon sink can be traded to other Member States or be used to compensate the effort sharing sector's emissions. One of the suggested principles to project historical forest management is to utilize the intensity of management (Grassi and Pilli 2017, Grassi et al. 2018), which is calculated by dividing the reference period's harvest by the amount of biomass that was available for the wood supply during the same period. The future harvest level is computed by keeping the intensity of management constant. This principle is used in Finland and in several other EU member states.

To analyse the suggested principle, we utilize a partial equilibrium model for forestry and agriculture (Mitra and Wan 1985, 1986, Salo and Tahvonen 2004). Using this model, we are able to compute a FRL in a case where policy shock has increased harvest levels after the reference period. This resembles the situation in Finland. Our numerical results show that the choices on the biomass available for wood supply, interest rate and the starting year of the projection can have significant impacts on the FRL computation. By these choices, a member state is able to overestimate the harvest possibilities. Thus, the EU fails to set a regulation that fully excludes national incentives in specifying the FRL. The setting of the Finnish FRL includes a tendency of minimizing the restrictions on the future harvest levels. This outcome follows by choosing high interest rate, early starting year for the projection and a loose definition for the biomass available for wood supply.

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LULUCF regulation, European Union, climate policy, Paris Agreement, incentives, carbon sink, forest reference level

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Tiivistelmä/Referat – Abstract

Työ analysoi metsien hiilinielun vertailutasolaskentaa Suomessa. Vertailutasot ovat osa EU:n uutta maankäytön, maankäytön muutoksen ja metsien (LULUCF) hiilidioksidipäästöjen tilinpidon määrittävää asetusta (EU 2018/841). Asetus on osa EU:n toimista, kohti Pariisin Ilmastosopimuksen tavoitteita. Tutkimus perustaa kirjallisuuskatsauksessa LULUCF asetukseen, vertailutason laskemisen ohjeistukseen, kansallisiin vertailutasoihin ja olemassa oleviin tutkimuksiin. Metsien päästöjä laskettiin vertailutasojen avulla jo Kioton pöytäkirjan toisella velvoitekaudella, mutta nämä epäonnistuivat liittämään metsät osaksi ilmastopolitiikkaa. Jäsenvaltioilla oli kannustin ilmoittaa mahdollisimman korkeat hakkuut vertailutasoissa (Frieden et al. 2012). Vertailutasoprojektiot sisälsivät oletuksia tulevaisuuden metsien käytöstä ja osa niistä ei koskaan toteutunut. Projektioissa hiilinielut jäivät liian pieniksi, mikä johti ansaitsemattomiin hiilikrediitteihin (Grassi et al. 2018, Krug 2018). Myös Suomen vertailutaso osoittautui epätarkaksi Kioton pöytäkirjan toisella velvoitekaudella. Tämä tutkimus analysoi pystyykö uusi LULUCF-asetus välttämään Kioton pöytäkirjan toisen velvoitekauden ongelmat metsien vertailutasoissa.

LULUCF-asetus on säädetty velvoitekaudelle 2021-2030. LULUCF-sektori ei saa asetuksen mukaan olla päästölähde. Metsien vertailutaso on projektio metsien hiilinielusta, joihin velvoitekauden hiilinielua vertaillaan. Vertailutaso tulee laskea niin, että se perustuu vertailukauden 2000-2009 toteutuneisiin metsänhoidon käytänteisiin. Vertailutasossa tulee ottaa huomioon metsien ikäluokkarakenne. Vertailutason avulla voidaan määrittää hakkuiden määrä, joka ei aiheuta päästöjä tilinpidossa. Jäsenvaltiot voivat käydä kauppaa lisäisestä hiilinielusta tai käyttää sen taakanjakosektorin päästövähennystavoitteiden saavuttamiseksi. Yksi ehdotettu periaate laskea vertailutaso, joka ilmentää historiallisia metsänhoidon käytänteitä, on perustaa laskelma historialliseen metsänhoidon intensiteettiin (Grassi ja Pilli 2017, Grassi et al. 2018). Tämä saadaan jakamalla vertailukauden toteutuneet hakkuut käytettävissä olevalla biomassalla. Vertailutaso on laskettu pitämällä metsänhoidon intensiteetti vakiona. Tätä periaatetta on käytetty Suomen ja monen muun jäsenvaltion vertailutasolaskelmissa.

Ehdotetun periaatteen arvioimiseksi, käytämme markkinatason osittaistasapaino mallia (Mitra ja Wan 1985,1986, Salo ja Tahvonen 2004). Malli kuvaa tilannetta, jossa jäsenvaltion hakkuut ovat nousseet vertailukauden jälkeen. Tämä kuvaa kehitystä, joka on tapahtunut Suomessa uuden metsälain jälkeen. Tutkimme numeerisin analyysin avulla mallin oletusten vaikutuksia vertailutasoon. Tulosten perusteella valittu korko, projektion aloitusvuosi ja hakkuukypsyyden määritelmä vaikuttavat vertailutasoon. EU:n LULUCF asetus ei kykene estämään kansallisten kannustimien vaikutusta vertailutason laskentaan. Suomen metsien vertailutaso on laskettu niin, että se rajoittaisi hakkuita mahdollisimman vähän. Tulokseen on päästy valitsemalla korkea korko, aikainen projektion aloitusvuosi sekä löysä hakkuukypsyyden määritelmä.

Avainsanat – Nyckelord – Keywords

LULUCF asetus, Euroopan Unioni, ilmastopolitiikka, Pariisin ilmastosopimus, kannustin, hiilinielu, metsien vertailutaso

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1 Introduction

The European Union adopted the new land use, land-use change and forestry (LULUCF) sector regulation (2018/841) in 2018, which sets the rules for the carbon emissions accounting in the sector. The regulation will be in force for the compliance period of 2021 to 2030. The regulation includes the LULUCF sector in the EU's climate policy alongside the EU-ETS and the effort-sharing sectors. The regulation is part of achieving the EU's Paris Agreement target, to be carbon neutral by the second half of this century. The Paris Agreement recommends its parties to preserve and enhance carbon sinks (UNFCCC 2015). Thus, forest carbon sinks are an important part of the global climate policy. The parties of the Paris Agreement agreed to limit the global warming below 2 degrees and to pursue limiting the warming to 1.5 degrees. The role of carbon removals is recognized as a major contributor to the pathways towards below two-degree global warming by the Intergovernmental Panel on Climate Change (IPCC 2018). The EU's LULUCF regulation aims to preserve and enhance forest carbon sinks by utilizing forest reference levels. The forest reference levels failed to incentivize climate mitigation in the forests during the Kyoto Protocol (Krug 2018, Grassi et al. 2018). It is still uncertain how this new regulation manages to avoid the same result, as the forest reference levels are produced nationally by the member states. Our study applies a market-level partial equilibrium model to study the modelling assumptions in the forest reference level projection.

The forests carbon sinks have a major climate change mitigation potential. In most of the presented pathways towards below two-degree warming the carbon removals are produced by forests (IPCC 2018). The time frame to mitigate the climate without massive carbon removals from the atmosphere is rapidly narrowing, but still the majority of the known carbon dioxide removal technologies need a lot of research and development (Smith et al. 2016). The growing forest biomass is considered to be a low cost and functional way to remove carbon from the atmosphere (EASAC 2018), which makes the role of the LULUCF sector important. The carbon sinks of the LULUCF sector have also been recognized in the EU's long-term strategy towards climate neutral economy (The European Commission 2018). Despite its recognized climate mitigation abilities, the LULUCF sector has been one of the most debated and complex sectors to be included in the climate policy (Krug 2018). The LULUCF sector is not only a carbon sink on the global scale. According to the IPCC's report *Climate Change and Land* (2019), 23% of the global emissions were from the LULUC sector between 2007 and 2016. The average annual carbon sink of forest land in the European Union was -414 $MtCO_2$ between 2000 and 2009 (EEA 2019).

Even though the Paris Agreement emphasizes carbon removals, it does not define any exact set of rules for carbon accounting in the LULUCF sector (Krug 2018). The parties of the Paris Agreement have defined the LULUCF policies in their nationally determined contributions (NDC) towards the carbon neutrality target. Höhne et al. (2017) show that there are overall inconsistencies between the NDCs, and Grassi et al. (2017) argue that these inconsistencies can also be seen in the LULUCF sector accounting methods. The LULUCF sector has not been properly included in the EU climate policy before, because of reporting uncertainties, national circumstances (e.g. state of the forests), and the possibility of unearned carbon credits that could harm the entire carbon accounting system (Krug 2018).

The UNFCCC, the IPCC and the global scientific community have held multiple discussions about the policies related to the carbon sink of the biomass during the last two decades (Krug 2018). First attempt to include forest carbon sink in the global climate policy was the first commitment period of the Kyoto Protocol (2008 – 2012) (UNFCCC 1998). Carbon accounting for forest management was voluntary and parties had multiple accounting options. The parties were able choose an accounting method that was favorable to the state of their forest. The usage of carbon credits to achieve climate targets was capped. However, the voluntary gross-net accounting created carbon credits that were not earned by real mitigation efforts (Krug 2018). The accounting rules for the Kyoto Protocols first period were a result of complex political negotiations and the result was not successful (Schlamadinger 2007).

The second Kyoto commitment period (2013 – 2020) had an improved and mandatory accounting approach for the forest management. Emissions and removals from forest management were accounted against a forward-looking baseline called the forest management reference level (UNFCCC 2011). The carbon sink created carbon credits if it was greater than the reference level. The usage of credits was capped also during the second commitment period. The reference levels were meant to project a business-as-usual-scenario (BAU), but the parties were able to include assumed future policy changes in their projections, e.g. assumed increases in harvest levels due to increasing biofuel demand. Information on the forest management practices and forest age-structure were used to calculate the reference levels. Even though the accounting rules were renewed, the old problems remained. It was unclear which historical data should be used to determine historical management practices that would define the business-as-usual level (Krug 2018).

The adopted policy did not lead to effective climate policy. The parties of the Kyoto Protocol had an incentive to report high harvest level in their reference levels (Frieden et al. 2012). However, many of the policy assumptions that anticipated increasing harvest levels never materialized, which led to unearned carbon credits (Grassi et al. 2018, Krug 2018). The reference levels did not have any restricting or carbon sink enhancing effect on the parties. The Kyoto Protocol failed to incentivize its parties to enhance carbon sinks, because additional carbon sequestration could not be fully included in the carbon accounting due to a cap (Krug 2018). If the carbon credits are capped, this reduces incentives to enhance carbon sequestration (Laturi et al. 2016).

An example of the failed Kyoto protocol forest management reference level projection was produced by Finland. It was estimated that the business-as-usual average annual carbon sink is -20.5 Mt CO_2 for the Kyoto Protocol's second commitment period (Ministry of Agriculture and Forestry, Ministry of Environment and Forest Research Institute 2011). The actual carbon sink from forest management has been greater during the Kyoto's second commitment period (Statistics Finland 2018). According to the carbon accounting rules this would have been considered as carbon credits. However, there has been no active policy efforts in Finland to enhance forest carbon sinks during this period. This leads to question whether the forest management reference level was projected correctly and whether it predicted the real business-as-usual development.

There have been arguments for not including forests in the carbon accounting system due to the problems occurred in the past (Krug 2018). The European Union did not account the obtained carbon credits from LULUCF sector to fulfill their climate targets for Kyoto's first period, and still it managed to reduce an extra 8% of emissions (The European Commission 2019a). Failed LULUCF policies have led to a situation where no additional mitigation has been undertaken by the forest management in Europe (Naudts et al. 2016). However, Krug (2018) sees the Paris Agreement as a "game changer" for the forest carbon sink in the climate change mitigation, because the parties of the agreement are able to include them as part of their NDC. This creates a new situation for the forestry sector where the parties try to figure out how to use forests as a resource for a bio-based economy, wood products and carbon sequestration. Krug (2018) also argues that the currently discussed accounting system for LULUCF is not yet sufficient and that the parties of the Paris Agreement need to consider the related issues in their NDCs.

The European Union continues to account emissions from the managed forestland in the spirit of the Kyoto Protocol, using revised version of the forest reference levels (FRL). The EU's new LULUCF regulation 2018/841 forbids the member states to include any future policy assumptions in their forest reference levels. The LULUCF sector's role is to provide carbon removals, which can offset emissions from other sectors of the EU climate policy (EU 2018/841). For the LULUCF sector, a 'no debit' rule is applied which means that all emissions from the sector need to be compensated by the member states. Compensation can happen by buying carbon credits from other member states or by equal carbon emission reductions in the effort-sharing sector. A limited number of possible LULUCF credits can be transferred to balance effort-sharing sector's emissions. The regulation is meant to encourage the member states to enhance their carbon sinks. (EU 2018/841.)

Previously LULUCF policies have not been incentivizing carbon sink enhancement but instead providing a framework for comparison (Krug 2018). Despite the fact that the regulation EU 2018/841 itself emphasizes carbon sink enhancement; it seems unclear whether it can give true incentives towards this goal for the member states. There are no existing studies on how the regulation performs compared to the Kyoto Protocol's forest management reference levels. The aim of this study is to find out if the LULUCF regulation is able to avoid the problems of the Kyoto Protocol in the national forest reference levels and include forests in the climate policy in an accurate and credible way. In the following chapters we study the concept of forest reference level (FRL). We aim our focus to the Finnish FRL, since it is produced by the recommended methods and principles. The Finnish FRL has gone through many changes and gives us a chance to evaluate how these changes have affected the results. To study the FRL we use an economic market-level forestry model to produce an FRL for a hypothetical member state that has experienced similar changes compared to Finland. We conduct a numerical analysis on the model choices to see their role in specifying the FRL results.

2 Forest reference level projection

Emissions from managed forest land are accounted by a net-net approach similar to the one used during the Kyoto Protocol's second commitment period. Actual emissions are accounted against a forward-looking forest reference level (FRL). If the actual sink is greater than the FRL the member state gains carbon credits. If the actual sink is lower than the FRL carbon sink the member state is considered to produce emissions. Because of the net-net accounting, a net carbon sink in the greenhouse gas inventory can also be considered as emissions in the case where actual sink is smaller than the forest reference level (EU 2018/841). Each member state must produce a National Forestry Accounting Plan with a forest reference level proposal, these are examined and approved by the European Commission (EU 2018/841). The FRL defines a baseline for the national forest carbon sink. Any deviation from the reference level is accounted either as emissions (debits) or as excess removals (credits). On the whole EU level, the use of carbon credits is capped to 280 Mt CO_2 per year. According to Grassi et al. (2017) the forest carbon sink is one of the key components of achieving the NDC targets and this demands transparency and confidence in numbers. This requirement is considered in the EU's LULUCF Regulation 2018/841 as it demands "*transparent, accurate, consistent, complete and comparable*" information on the greenhouse gas inventories in order to monitor the fulfillment of the regulation.

As mentioned, the reference levels were inaccurate during the Kyoto Protocol due to the inclusion of assumptions on the future policies (Krug 2019, Grassi et al. 2018). Now the EU tries to avoid the past mistakes and the forest reference levels must be based only on the historical forest management practices of the reference period 2000 – 2009 and on the age structure of the forest (EU 2018/841). Thus, the forest reference level resembles a situation, where the future forest would be managed according to the historical practices. There is no trivial solution to how the historical management practices should be applied in the FRL projection. However, one principle is presented by Grassi and Pilli (2017) and Grassi et al. (2018), who propose to project the reference level by keeping the historical "*intensity of management*" IM_{RP} constant for the harvest level. Following the notation in Grassi and Pilli (2017) the value for IM_{RP} is calculated as follows

$$IM_{RP} = \frac{H_{RP}}{BAWS_{RP}},$$

where H_{RP} denotes the reference period's total harvest amount and $BAWS_{RP}$ denotes the biomass that was available for wood supply during the reference period (RP). Biomass is considered "*available for wood supply*", when it reaches certain criteria (e.g. diameter or age). By keeping intensity constant, the absolute harvest levels can still fluctuate by age-structure dynamics. Hence, intensity does not mean an absolute quantity limit on harvests defined by the reference period. Grassi et al. (2018) describe their principle as "*science - based and credible*". Their motivation was to form a method that eliminates the effect of any expected future policy changes that made the Kyoto forest reference levels inaccurate. However, it remains somewhat unclear what kind of incentives the proposed principle creates for the member states FRL projections. The described principle is applied in many FRLs produced by the member states, e.g., in Finland (Natural Resources Institute Finland and Ministry of Agriculture and Forestry, 2019).

In addition to the requirements on forest management practices, the LULUCF regulation (EU 2018/841) has a set of additional criteria that the member states must fulfill: the applied forest management practices must be sustainable, the FRL has to be in line with the GHG inventories, carbon accounting needs to be robust and credible, the carbon pool of harvested wood products has to be included in and take decay and half-life values into account, and the ratio between energy and solid use of wood has to be constant. The member states must produce a forest reference level that is in line with the EU's climate mitigation targets set by the Paris Agreement (EU 2018/841).

The regulation document itself does not provide any in-detail instructions on how to produce the forest reference level. However, Directorate-General for Climate Action has released a guidance document to help the member states produce the national forestry accounting plans and forest reference levels. This guidance document by Forsell et al. (2018) is a co-creation of three organizations: International Institute for Applied Systems Analysis (IIASA), Aether and ICF Consulting Limited (ICF). The document offers step-by-step guidance for the reference level projection. It guides the member states to project the reference level according to the historical forest management practices, without any assumed changes in future demand or land use. Forsell et al. (2018) present this procedure by six steps, which are presented in the following paragraphs.

As the first step the member state must divide the area into classes (e.g. by different geographic regions, ownership, accessibility etc.) (Forsell et al. 2018). They use these classes, called stratum, to identify the forest management practices in the second step. There can be multiple, differently managed, strata in a member state. This procedure is not mentioned in the regulation, but it helps to make the reference level projection more transparent. The used strata should be as consistent as possible with GHG inventories and without any systematic change over time. The member state should report from each stratum the area, age-related characteristics during the reference period and at the starting year of the FRL projection, and tree species of the stratum (Forsell et al. 2018).

The second step is to identify the prevailing forest management practices of the reference period 2000 – 2009 (Forsell et al. 2018). They ask the member state to define the management practices by each defined forest stratum. Forest management practices refer to all activities that are carried out during the forest's development (e.g. thinning and clear cut). It is important that the member state demonstrates when and how each management practice is carried out in each stratum. To demonstrate the state of the forest, the member state can use e.g. variables such as mean age or mean diameter. These can be used to determine the maturity of the stand. If there is an observable trend, e.g. decreasing rotation lengths, the average value of the reference period should be used in the projection (Forsell et al. 2018).

The third step for the member state is to choose the procedure to project the carbon pools' development (Forsell et al. 2018). The LULUCF regulation does not define the exact computation setup, only fulfilling the regulation's criteria is required. During the Kyoto Protocol's second commitment period the EU provided strong support for reference level computation and recommended certain models to be used. Hence, more than half of the member states used the G4M, EFISCEN and WoodCarbonMonitor models (Forsell et al. 2019). According to Forsell et al. (2018) member states should use state of the forest and management practices as a model input. Harvested area, harvested biomass and age structure are dynamic variables in the model, while the management practices are fixed variables. This means that for example the intensity of management (see Grassi and Pilli 2017, Grassi et al. 2018) is kept constant. Forsell et al. (2018) defines three ways to project the reference levels harvests: *"Maintain the harvest ratio to the wood available for cutting", "Maintain the harvest ratio to the total wood available"* and *"Maintain harvest amount"*. The last option is recommended only if there is a lack of available information, because it does not consider the dynamic age structure.

The fourth step is to calibrate the chosen methodology to be consistent with the GHG inventory (Forsell et al. 2018). They point two goals for this step. The first one is to show that the model produces an output that is consistent with greenhouse gas inventory and the second is that the modelled management practices are in line with the ones that were used during the reference period. It is suggested that the member states calibrate the applied model by comparing the results against reference period's (2000 – 2009) statistics and then apply the adjusted model to the compliance period (2021 – 2030).

The fifth step is to project the development of emissions and sinks from the managed forest land for the compliance period (2021 – 2030) (Forsell et al. 2018). The member states should start the projection as close to the year of 2009 as possible. If the starting year is later, it should be shown that the model can reproduce the historical values from the beginning of the reference period to the starting point projection. The latest information on the forest state should be used to define the initial forest state (e.g. latest NFI data). The member states may correct the projection until the beginning of the compliance period (2021), if the model's output forest state differs from the actual forest state. The FRL projection should not follow any observable trend that was taking place during the reference period. Thus, it can't be assumed, for example, that trend of increasing demand is continued in the FRL projection. (Forsell et al. 2018.)

The last step is to calculate the forest reference level, which is reported as annual averages for periods of 2021 – 2025 and 2026 – 2030 (Forsell et al 2018). The member states are only allowed to make technical corrections to the forest reference level after it is calculated. This could happen if the methodology for greenhouse gas inventories is updated. After such technical corrections the member states must show that the consistency holds. All other changes to the results are forbidden.

3 Impacts of the forest reference level computation choices

Forsell et al. (2019) studied the effects of the modelling assumptions on the national forest reference levels, using the WoodCarbonMonitor and G4M models. These models were also used for the forest management reference level projections during the Kyoto Protocol. They argue that the starting year of the projection, stratification of the managed forest land or the timing of management practices have a small impact on the FRL results. They point out that it is not clear whether the projection should start right after the reference period of from the latest inventory data. In their assessment they compared results between starting years of 2010 and 2015. When the starting year was further from the reference period, the timing of management practices and age structure of the forest had greater impact on the FRL. The aggregate results for the whole EU varied between -319 $MtCO_2$ and -397 $MtCO_2$, depending on the modelling assumptions.

According to the results in Forsell et al. (2019), the forest reference level projection is more sensitive to the model assumptions if the member state has experienced fluctuating harvest levels during the reference period. Member states with varying historical harvest patterns do not have unambiguously defined forest management practices, e.g. rotation lengths, for the reference period. Assumptions on forest management are considered to have more impact on the member states in Northern and Central-West Europe, like Finland, Sweden, Estonia, Germany, Austria, France and United Kingdom. The member states in Southern and Central-East Europe with more stable forest management are not as sensitive to the assumptions on forest management (Forsell et al. 2019).

The LULUCF regulation has raised concerns that the regulation would restrict the future wood supply in the EU. Nabuurs et al. (2018) studied the forest reference levels' effects on the EU wood supply, when the forest is managed according to the reference period's forest management practices. They used the EFISCEN European forest model. The EFISCEN model represents forest resources by area distributed in age and volume classes and the forest management regimes are defined exogenously (Verkerk et al. 2016). The results of Nabuurs et al. (2018) show that the harvest levels increase due to maturing forests. The harvests might even reach a level where they exceed the increment. The regulation (EU 2018/841) states that the FRLs must not violate sustainability criteria. Nabuurs et al. (2018) limited the harvest to be max 90% of the increment. Even with the restriction the aggregate harvest levels are expected to increase in the EU. They point out that the reference level results differ between the member states.

There was a debate in Journal of *Forest Policy and Economics* concerning the FRL's effect on wood supply. Kallio et al. (2018) argued that the LULUCF regulation would restrict the wood supply in the EU, because the reference period's harvest levels were lower than the anticipated future demand. Kallio et al. (2018) used the EFI-GTM partial equilibrium model, which included a restriction on average harvest levels defined by the reference period. The EFI-GTM is a multi-periodic, but static, partial equilibrium model, which calculates production, consumption, imports, exports and the product prices (Kallio et al. 2004). Grassi et al. (2018b) answered the critique and claimed that Kallio et al. (2018) misinterpreted how to apply historical forest management in FRL projection. Instead of using absolute maximum harvest levels, they should have considered the dynamic effects of the developing age-class structure and the available amount of growing stock. On the aggregate EU level, the harvests are expected to increase due to more forests reaching maturity in the near future (see e.g. Grassi et al. 2018, Nabuurs et al. 2018).

The Finnish Climate Change Panel report (Mutanen et al. 2019) analyzed the effects of age-class structure in the FRL projection. They presented eight cases where the managed forest land was allocated to age classes in different ways. Fluctuations in the age-class structure causes fluctuations in the projected harvest levels. If the age-class structure is skewed towards the older age classes (more forest in older age classes), the harvest levels are high in the future and vice versa. An evenly distributed age class structure, i.e. normal forest, results equally stable harvest levels between reference period and compliance period.

The LULUCF regulation 2018/841 aims to motivate the member states to enhance their carbon sinks. As we have learned from the past, it is not easy to determine whether the mitigation efforts are real or not in the LULUCF sector (see e.g. Krug 2018). The accounting approach for the LULUCF sector needs to be credible so that only real mitigation efforts are rewarded (Grassi et al. 2018). According to Laturi et al. (2016) the use of reference levels will benefit the climate policy targets only, if they restrict the harvest levels. If the LULUCF regulation does not lead to a situation where FRL harvest are lower than business-as-usual harvests, the policy will not result in any real climate change mitigation.

4 Finnish forest reference level

In Forsell et al. (2019) countries with large forestry sector were more affected by the modelling assumptions. Finland is a large consumer and producer in the forestry sector even on a global scale (FAOSTAT 2020). Thus, the Finnish FRL is likely affected by the modelling choices. So far, Finland has produced two versions of the forest reference level proposal, and the assumptions and results have changed between them. This makes Finland a good subject for our study. We focus on the description of the modelling choices concerning the commercial forest biomass. The Finnish FRL was produced by the Finnish Natural Resources Institute and the Ministry of Agriculture and Forestry. The first proposal was published at the end of 2018. After the first submission round the LULUCF expert group (LULUCFEG) commented the national forest reference levels and the European Commission (2019b) gave several technical recommendations for FRL revision. These recommendations are presented in detail later in this chapter.

The main results of the Finnish forest reference level (Natural Resources Institute Finland and Ministry of Agriculture and Forestry 2019.) for the years from 2021 to 2025 are that the forest carbon sink is -21.16 Mt CO_2 eq. and the corresponding harvest level is 77 mill m^3. Total forest reference level with the carbon pool of harvested wood products is -27.64 Mt CO_2 eq. These latest results have changed a lot from the first proposal, with a forest carbon sink of -27.88 MtCO_2 and harvest levels of 83.1 mill m^3 (Natural Resources Institute Finland and Ministry of Agriculture and Forestry 2018).

4.1.1 Forest management practices

In the first Finnish FRL proposal the Tapio (2006) silvicultural recommendations were used to define the reference period's forest management practices. This seemed problematic since it neglected the stricter legal limits than were in force at the beginning of the reference period (see Ministry of Agriculture and Forestry 1997, Tapio 2001). The European Commission (2019b) asked Finland, in the technical recommendations, to demonstrate if this assumption really demonstrates the forest management practices of the reference period. Also, the land-use, land-use change and forestry expert group (LULUCFEG 2019) required an explanation for this decision.

Table 1 presents the diameter limits that have been defining the maturity of the Scots Pine stands in Finland by law and silvicultural recommendations. The overall trend has been that the maturity limits have decreased during the past two decades. In the preliminary results for revised second FRL proposal (Lehtonen 2019) the mature stand limits were even lower (Table 1). This seemed problematic since they were clearly violating the binding legal limit that was used during the first years of the reference period. Rotation length was assumed to be shorter than the legal limit during the reference period. For the official results of the proposal (Natural Resources Institute Finland and Ministry of Agriculture and Forestry 2019) this was corrected and Forest Act (1997) and Tapio (2006) were used to describe the forest management of the reference period. If these two documents were in contradiction the one with the stricter (i.e. higher) limit was used. However, the silvicultural recommendations in Tapio (2001) suggests even longer rotation periods than the Forest Act (1997). These recommendations are still neglected in the las FRL proposal.

Table 1. Diameter limits (dbh) for mature stands

Scots pine	Forest Act 1997 -2006			Forest Act 2006-2014			Tapio 2001		Tapio 2006			Lehtonen 2019		
Site class	Other Finland	Kainuu and Pohjois-Pohjanmaa	Lappi	Southern Finland	Central Finland	Northern Finland	Southern Finland	Northern Finland	Southern Finland	Central Finland	Northern Finland	Southern Finland	Central Finland	Northern Finland
MT	27	25	23	25	23	22	29-31	26-29	26-32	24-28	23-27	25.5	24.5	22.5
VT	25	24	23	24	22	21	27-29	24-27	25-30	23-27	22-26	24.5	22.5	21.5
CT	23	22	22	20	20	20	25-27	23-25	22-26	22-25	21-25	21.5	21.5	20.5

Note. Data from Tapio (2001 and 2006), Ministry of Agriculture and forestry (1997 and 2006), Lehtonen (2019)

The identified forest management practices were used to calculate the intensity of management (Grassi and Pilli 2017, Grassi et al. 2018) in both versions of the forest level proposals. Finland defines the available biomass by the area under thinning and mature stand development classes. Development classes are defined by diameter limits (Table 1). Harvests are calculated for thinnings and final fellings separately (Natural Resources Institute Finland and Ministry of Agriculture and Forestry 2018 and 2019). In the first forest reference level proposal 6.7% (intensity of management) of the mature stands were harvested. In the preliminary results of the second proposal the intensity of management for mature stands changed to 6%, while the diameter limits were decreased (Lehtonen 2019). Since the amount of harvests is a statistical figure, the only thing that could change the historical intensity of management is the definition for mature stands. Intuitively, intensity decreased, because the number of stands that were considered mature increased. In the official results of the second proposal the intensity of management changed to 7%, and the mature stand limit was higher than in the preliminary results. These changes show that the definition for available biomass has an effect to intensity of management, which is one of the key parameters in the FRL projection.

The European Commission (2019b) asked Finland to provide information about the land allocated to each development class, so that the FRL harvest amounts are in line with the forests age-related dynamics. In the first FRL proposal the harvests were increasing and the only acceptable explanation for this, according to the regulation (2018/841) and the guidance document (Forsell et al. 2018), are the age-related dynamics of the forest, implying that the age-classes reaching maturity during the compliance period are larger. The second FRL proposal shows the allocation between development classes. The allocation for the years 2000, 2006 and 2011 are from the National Forest Inventory (NFI) results and for the rest of the years the allocation is an MELA model output. When the MELA output is compared with the NFI 12 results, it seems that the MELA output overestimates the number of mature stands and underestimates the number of thinning stands. This suggests that the forest state in the FRL projection may not reflect the reality at the beginning of the compliance period (2021).

4.1.2 MELA forest planning system

The forest reference level is projected by using the MELA model, which is a detailed age-structured forest planning model with optimization but without endogenous market prices (Redsven et al. 2012, Hirvelä et al. 2016). The model projects the reference level by keeping the forest management practices (limits and intensity) at the level of the reference period. The model uses the year 2016 as a starting point, so the forest state for the beginning of the compliance period is already a MELA model output. As a sustainability measure the Finnish FRL assumes non-declining harvest levels for the years 2016 – 2061. After defining the restrictions, the model was used to describe how the forest resources would develop. In the Finnish FRL proposal (Natural Resources Institute Finland and Ministry of Agriculture and Forestry 2019), the intensity of management restriction for final fellings and thinnings is written as

“$\textit{Thinning area}_t < \textit{tha\%}_{(2000\text{-}2009)} * \textit{Area of young and advanced thinning stands}_{tb,}$

$\textit{Final felling area}_t < \textit{ffa\%}_{(2000\text{-}2009)} * \textit{Area of mature stands}_{tb}$ “, where *tha%* and *ffa%* denote harvested are from thinnings and final fellings during the reference period respectively.

For the biodiversity the MELA model is constrained by four assumptions in the revised FRL proposal. The projection must leave five cubic meters worth of retention trees per hectare. Harvesting dead wood is not allowed. Clear cuts are not allowed in the forest land available for restricted wood supply or in the low productive forest lands (scrub land). The biodiversity assumptions were questioned after the first FRL proposal by the European Commission (2019b) because of the increasing harvests (83.1 mill m^3). In the revised proposal the harvest levels are lower (77 mill M^3), but still higher than during the reference period (see Figure 1).

4.1.3 Interest rate

In the MELA model, interest rate is one of the key parameters. An interest rate of 3.5% is applied in the FRL projection. Natural Forest Resources Institute Finland (Lehtonen et al. 2018) conducted a sensitivity analysis on the effects of the interest rate. Interest rates of 2.5, 3.0, 3.5 and 4.0 were tested and yielded harvest amounts of 70.7, 77.6, 83.1 and 87.6 mill M^3. In the MELA model's net present value calculation the forest can be harvested when its value increment is below the interest rate (Redsven et al. 2012). In the Faustmann (1849) formula-based forest rotation optimization, a higher interest results in shorter optimal rotation periods. According to the MELA2016 Reference manual (Hirvelä et al. 2016) the discount rate is expressing "the real annual rate of compound interest".

In the first FRL proposal the explanation for the decision of the 3.5% discount rate was that the real investment return in forestry was 3.58% during the reference period and is therefore the best interest rate to describe forest owner's decisions. The European Commission (2019b) asked Finland to demonstrate that the interest rate is suitable for describing all the actions carried out during the reference period. There are more than 600 000 forest owners in Finland, and 60% of the forests are privately owned (Leppänen and Torvelainen 2015). Thus, with such versatile group of actors, questioning the suitability of the chosen discounting interest rate seems justified. The second FRL proposal compares MELA output with different interest rates against the reference period values, and the interest rate of 3.5% is said to be the most appropriate to describe the years 2000 – 2009.

The second proposal gave a new explanation for the applied discounting interest rate. It is said to describe the risk related to forest investments. The interest rate was calculated by concept called “The Capital Market Line” (CML). The idea for CML is presented in Sharpe (1964). CML shows the investment portfolios that optimally combine risk (volatility) and real rate of return. It reveals the trade-off between the risk (volatility) and return. Optimally the investor chooses the investment combination from the CML which is tangent to the efficient investment frontier. Hyytiäinen and Penttinen (2008) studied the effects of portfolio optimization on harvesting decision. In their analysis the rate of return for forest stands is 3-4% and it falls under the efficient investment frontier. In their study the efficient portfolios with the same volatility as forest stand investments had around 6% rate of return. If the efficient portfolio offers a higher rate of return with the same volatility, it would be more profitable investment option. Traditionally forest economic analysis applies interest rate equal to the rate of return from the best alternative investment option in competitive capital markets (Samuelson 1976). This kind of reasoning suggests that the rate of return of the efficient portfolio, could be applied as the interest rate. However, in Finland, decisions on forest management have been mostly driven by the objective of maximum sustainable yield (MSY), which is optimal when interest rate is approximately zero (Hyytiäinen and Tahvonen 2003). Thus, interest rate of 6% or even 3.5% seems to be too high to describe traditional Finnish forest management.

There are many other arguments that can be presented against the applied interest rate of 3.5%. In the silvicultural recommendations Tapio (2006), a real interest rate of 2-3% was suggested to be applied in forest management. This is lower than the interest rate used in the FRL proposal. Interest rate of 3.5% would have led to illegal rotation lengths at the beginning of the reference period (Hyytiäinen and Tahvonen 2001). In the background calculations for Tapio (2006) silvicultural recommendations most of the suggested maturity limits were optimal only with interest rates of 1-2% (Hyytiäinen et al. 2010). Penttinen (2006) studied the effects of stochastic price growth volatility for optimal rotations lengths for Scots Pine stands and found that interest rates exceeding 3.5% violated the Forest Act (1997), and that the Tapio (2001) silvicultural recommendations were suggesting rotation lengths that were not economically optimal.

4.1.4 Comparison with the GHG inventories

The guidance document by Forsell et al. (2018) underlines that the selected model must be able to produce the historical GHG inventory data. The first FRL proposal compared the MELA model output with GHG inventories between 2011 and 2016, but not with the reference period. The second proposal shows a comparison between the MELA model output and the GHG inventories between 2005 and 2010, but not for the whole reference period. The comparison with the years 2000 – 2004 was left out, because the MELA model results are affected by the initial state at the beginning of the projection. The MELA model produced an output that was closest to the 2005 – 2010 average annual harvest levels with the interest rate of 3.5%. The output and statistics do not match perfectly, so the model is corrected by an ex-post calibration factor. The second proposal does not show how the output matches the realized statistics between the reference period and compliance period. From the results presented in proposal's appendix section we can observe that the MELA model projects higher numbers of mature stands (3 mill ha) than there were in latest NFI 12 (2.17 mill ha).

The guidance document (Forsell et al. 2018) suggests that the member state should provide a proper comparison between the model output and the GHG inventories of the reference period. This is recommended, because it shows that the model is capable to produce accurate estimates of the forest development. Forsell et al. 2018 also suggests that, if the FRL projection starts later than 2010 the comparison should be provided up to the starting year. In the guidance document it is also suggested that the member states may conduct a technical correction, to match the model output and actual forest state up to the year 2021. This technical correction seems to be left undone in the Finnish FRL and the starting point for the FRL is a MELA model output, which has an overestimated number of mature forest stands.

4.1.5 Forest policy changes in Finland

The management and state of the forest land has experienced many changes between the years 2000 and 2020. It seems that silvicultural recommendations by Tapio and the Forest Act have had a strong influence on the forest owner's management decisions in Finland. The trend in silvicultural recommendations (Tapio 2001, 2006 and 2014) has been that the forest owners have gained more freedom in decision making. The diameter limits for regenerating the forest were removed from the new Forest Act (2014) (Ministry of Agriculture and Forestry 2013). In practice, these new guidelines and the new law have resulted in, for example, shorter forest rotations. There are already many observable changes in the Finnish forest structure. The number of mature stands has decreased in the Finnish national forest inventories (NFI) (Table 2) and the harvest rates have increased after the RP (Figure 1). Some of the forest areas in Southern Finland have even been emission sources during the past few years (Natural Resources Institute Finland 2019).

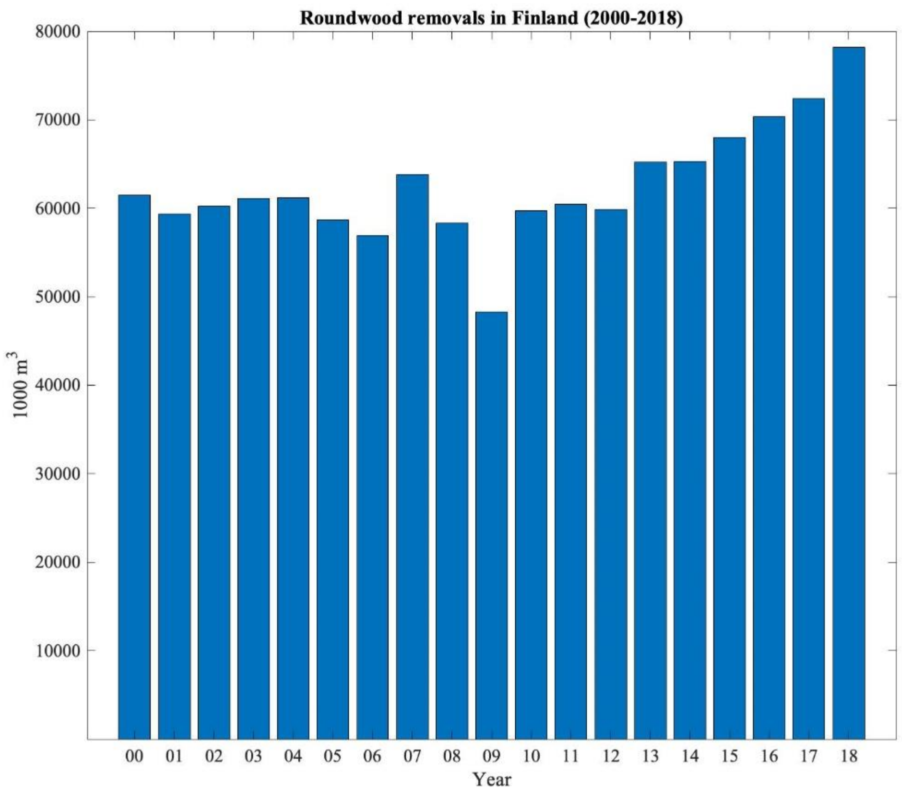

Figure 1. Harvest in Finland (2000-2018). Data from Natural Resources Institute Finland (2018).

Table 2. Land area for mature stand development class in Finland

	Mature stand development class (1000 ha)
NFI 9 (1996-2003)	2601
NFI 10 (2004-2008)	2529
NFI 11 (2009-2013)	2408
NFI 12 (2014-2018)	2168

Note. Data from Natural Resources Institute Finland (2017)

5 Analyzing the forest reference level computation setup by a market-level economic model

For this thesis, we chose a market-level partial equilibrium model, first introduced by Johnson and Scheurman (1977) and later studied in economics by Mitra and Wan (1985, 1986). The model was later extended by Salo and Tahvonen (2004) to include land allocation, which smoothens or vanishes the cyclical solutions of the original model. Cunha-e-Sa et al. (2013) and Tahvonen and Rautiainen (2017) included carbon storage in the model. The model allows us to present the transitional development of forest structure and wood supply. Thus, we are able to develop a forest reference level for our hypothetical case where harvest levels have increased after the reference period, like in Finland. The model allows us to simulate the setup and the restrictions of the LULUCF regulation.

Forest land is divided to age classes $s = 1,...,n$ where all stands aged n or older are allocated to age class n. The share of forest land allocated to each age class s in period t is denoted by x_{st}. The area allocated for agriculture is denoted by y_t. The total land area equals one. The volume of commercial timber in age-class s is denoted by f_s, and it is assumed that $0 \le f_1 \le ... \le f_n$. The inverse demands for timber and agriculture are denoted by $D_c(c_t)$ and $D_y(y_t)$. Thus, utility functions can be given as $U(c_t) = \int_0^{c_t} D_c(c)dc$ and $W(y_t) = \int_0^{y_t} D_y(y)dy$. The utility functions are assumed to be strictly concave, continuous, twice differentiable and increasing. The discount factor is denoted by $b, (0 < b < 1)$.

Timber is harvested at the end of each time period t and total harvest is written as

$$c_t = \sum_{s=1}^{n-2} f_s(x_{st} - x_{s+1,t+1}) + f_n(x_{nt} + x_{n-1,t} - x_{n,t+1}) . \qquad (1)$$

The total cost of regenerating forest land in each period is determined by multiplying the share of regenerated land $x_{1,t+1}$ with regeneration cost w.

The optimization problem

The social maximization problem is given as

$$\max_{\{x_{st}=1,2,\ldots,n;t=1,2,\ldots\}} W = \sum_{t=0}^{\infty} b^t [U(c_t) + W(y_t) - wx_{1,t+1}] \tag{2}$$

subject to

$$y_t = 1 - \sum_{s=1}^{n} x_{st} \tag{3}$$

$$x_{s+1,t+1} \leq x_{st}, s = 1,\ldots,n-1 \tag{4}$$

$$\sum_{s=1}^{n} x_{s,t+1} \leq 1 \tag{5}$$

$$x_{st} \geq 0, s = 1\ldots,n \tag{6}$$

for all $t = 0,1\ldots$, where the initial conditions satisfy

$$x_{s0} \geq 0, s = 1,\ldots,n, \sum_{s=1}^{n} x_{s0} \leq 1. \tag{7}$$

The objective function maximizes total utility of land use. In each period, the problem is to choose the harvest level from each forest age-class and the allocation of bare land between land-classes. Tahvonen and Rautiainen (2017) also include the forest carbon sink in the objective function. In our case we only observe the development of carbon sink without including it in the optimization. The per period present value V of forest net carbon sink is written as

$$V_t = b^t [\tau [\sum_{s=1}^{n} f_s (x_{s,t+1} - x_{st}) + (1-\beta)c_t]]. \tag{8}$$

The carbon net-flow depends on the change in the wood volume and the share of land allocated to corresponding age classes. The social price of CO_2, denoted by τ, is exogenous. The carbon pool of harvested wood products is calculated as $(1-\beta)c_t$, where β is determined by the decay rate of harvested wood products. For simplicity purposes, we assume $\beta=1$ and study only the carbon sink of living trees.

The optimality conditions

The Lagrangian for the problem (1) – (7) is

$$L=\sum_{t=0}^{\infty} b^t \left\{ U(c_t)+W(y_t)-x_{1,t+1}w+\lambda_t(1-\sum_{s=1}^{n} x_{s,t+1})+\sum_{s=1}^{n-2}\mu_{st}(x_{st}-x_{s+1,t+1})+\mu_{n-1,t}(x_{nt}+x_{n-1,t}-x_{n,t+1}) \right\},$$

where λ_t and μ_t are the Lagrangian multipliers. The Karush-Kuhn-Tucker conditions for $t=0,1,...$ are

$$b^{-t}\frac{\partial L}{\partial x_{1,t+1}}=bf_1U'(c_{t+1})-bW'(y_{t+1})-w-\lambda_t+b\mu_{1,t+1}\leq 0, \tag{9}$$

$$b^{-t}\frac{\partial L}{\partial x_{s+1,t+1}}=-f_sU'(c_t)+bf_{s+1}U'(c_{t+1})-bW'(y_{t+1})-\lambda_t-\mu_{st}+b\mu_{s+1,t+1}\leq 0,\ \text{for } s=1,...,n-2, \tag{10}$$

$$b^{-t}\frac{\partial L}{\partial x_{n,t+1}}=-f_nU'(c_t)+bf_nU'(c_{t+1})-bW'(y_{t+1})-\lambda_t-\mu_{n-1,t}+b\mu_{n-1,t+1}\leq 0, \tag{11}$$

$$x_{s,t+1}\geq 0, x_{s,t+1}\frac{\partial L}{\partial x_{s,t+1}}=0, s=1,...,n, \tag{12}$$

$$\mu_{st}\geq 0, \mu_{st}(x_{st}-x_{s+1,t+1})=0, s=1,...,n-2; \mu_{n-1,t}(x_{nt}+x_{n-1,t}-x_{n,t+1})=0, \tag{13}$$

$$\lambda_t\geq 0, \lambda_t(1-\sum_{s=1}^{n}x_{s,t+1})=0. \tag{14}$$

Salo and Tahvonen (2003) prove that a cyclical stationary state exists for any number of age-classes when all land is allocated to forestry. In Salo and Tahvonen (2004) it is shown that the cycles vanish and the forest state approaches a unique steady state where land is allocated between forestry and an alternative land use. In what follows the model is computed as a nonlinear programming problem applying AMPL programming language and Knitro optimization software (version 12.3) with a horizon length of 200 periods where period length is 5 years.

Computation setup for the numerical analysis

The chosen model is used for numerical analysis to study how the forest reference level depends on 1) the starting year of the projection, 2) applied interest rate and 3) the BAWS definition. The choices on these definitions play an important role in the Finnish FRL computation. The Finnish forestry sector has experienced big policy changes after the reference period. The rotation lengths are not restricted in the new policy and the harvest levels have increased. Despite of these changes the reference level must be based on the forest management practices applied during the reference period. To understand the implications of this setup, we apply the market-level model and include a similar policy change after the reference period. First, we need a description of the actual forest development from the beginning of the reference period to the beginning of the compliance period. This description is created with the model and defines the actual forest development of our hypothetical case.

First, we run the model to compute the reference period data for both scenarios separately. To be consistent with the 5-year time periods of our model, the reference period in our numerical example is 2001 – 2010. In both scenarios the reference period's forest management is restricted and harvesting the forest is not allowed from the age classes below 11. In our setup this yields a situation where forest rotations are longer than the optimal rotation. Harvesting age class 11 is an optimal solution, with market interest rate of 1%. We assume that the real market interest rate is 4%. This mimics the situation in Finland during the reference period, when applied forest rotations were longer than the economically optimal rotations. We carry out the computation for two different scenarios with a different age-class structure, to ensure robust results. Scenario 1 represents a situation where forests are in a normal forest state during the reference period. Scenario 2 represents a situation where old age classes dominate the forest structure during the reference period. By considering scenarios 1 and 2, we can detect whether the analyzed computation choices on 1) - 3) have similar effects in both scenarios despite the differences in the age-class structure.

After the reference period, the restriction for the harvest age is removed. Similar development has been undertaken in Finland after the reference period. Next we compute how the age-class structure of the forest starts to shift towards an unrestricted state, where the forest rotation is determined by the market interest rate equal to 4%. This procedure defines how the age-class structure develops between the reference and the compliance period. In our setup, we call this period between the reference and compliance period as a transition period. In our computation the policy change yields a shorter forest rotation for the transition period, which mimics the policy change in the Finnish forest management.

We use the simulated data on the reference and transition period to compute the forest reference level for our hypothetical case. First, we calculate the intensity of management for all BAWS definitions as presented in Grassi et al. (2018) from the reference period. The lower limit for BAWS is denoted by q. All of the age classes older or equal to q are considered to be available for wood supply. For example, if $q=1$ all age classes are considered to be available for wood supply. Intensity of management is the ratio between historical harvests and the biomass that was available for wood supply, and is calculated as

$$\alpha_q = \frac{\sum_{s=q}^{n-2}\left(x_{st} - x_{s+1,t+1}\right) + \left(x_{nt} + x_{n-1,t} - x_{n,t+1}\right)}{\sum_{s=q}^{n} x_{st}}, \tag{15}$$

where α_q is the intensity of management for different BAWS definitions and $q=1,...,11$.

The LULUCF regulation (EU 2018/841) does not define any specific starting point for the FRL computation. In the provided guidance document by Forsell et al (2018) it is suggested that the member states start the forest reference level computation as close to the reference period as possible. However, it is also suggested that the used data should be the best available data describing the state of the forest. Thus, if the age-class structure has changed notably after the reference period, the actual state of the forest at the beginning of the compliance period should be applied as a starting point. In our setup, the simulated transition period defines the actual forest development for 2011 – 2020. Thus, it shows us the state of the forest, i.e. age-class structure, at the beginning of the compliance period.

We consider two FRL computation options concerning the starting year. A timeline illustration of the logic behind the two options is presented in Figure 2. In option A the forest reference level computation starts from the beginning of 2016 and uses the corresponding actual age-class structure as a starting point. In option B, the starting year is 2021 and the corresponding actual age-class structure is used as a starting point. The main difference between the computation options is the starting year after which the forest development is an constrained model output, i.e. in option A forest development is computed using the FRL restrictions from the beginning of 2016. If the model output in option A for 2016 – 2020 is not consistent with the transition period, the FRL is based on a unobservable forest state.

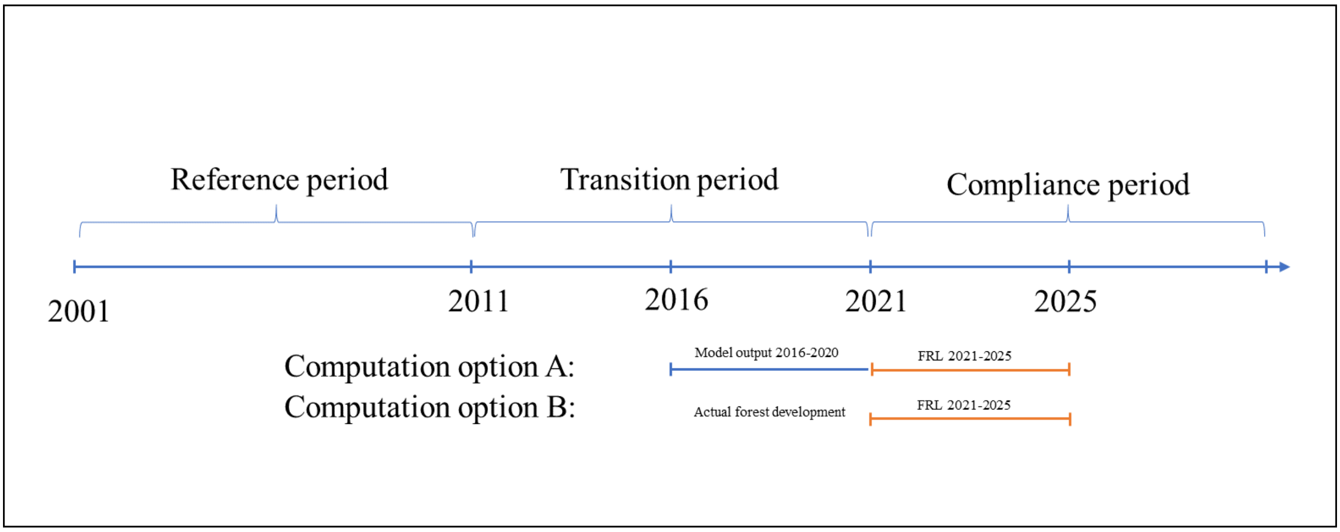

Figure 2. Timeline for the computation setup

In both computation options we consider all the possible BAWS definitions and interest rates of 1,2,4 and 8 %. For the both computation options the model is restricted by the intensity of management and harvest is not allowed from age classes below the BAWS definition limit. Intensity of management is computed by the equation (15). For the harvest level the following equations must hold

$$c_t \leq \alpha_q \sum_{s=q}^{n} x_{st} , \tag{16}$$

$$c_t = \sum_{s=q}^{n-2} f_s (x_{st} - x_{s+1,t+1}) + f_n (x_{nt} + x_{n-1,t} - x_{n,t+1}) , \tag{17}$$

where $q = 1,...,11$. Hence, by equations (16), it is only allowed to cut the intensity of management defined share of the stands that are considered available for wood supply. By equation (17) it is only allowed to cut stands that are considered available for wood supply. By following the described computation setup above we are able to analyse how the choices on 1) - 3) affect the forest reference level, when there has been a harvest increasing policy change after the reference period.

6 Results

The actual age-class structure development, in both scenarios, from the end of the reference period until the beginning of compliance period is presented in Figure 3; Scenario 1 in A – C and Scenario 2 in D – F. Figure 3 B – C and E – F represent the transition period. In both scenarios the age-class structure starts to shift towards a shorter rotation after the policy change at the end of the reference period. The change in rotation lengths is not immediate in all forest land i.e. the share of land in older age classes begin to decrease gradually. In scenario 1, the change is the most drastic, since the whole 11th age class is cut down before the compliance period. From the simulated reference periods we obtain the intensity of management for all of the BAWS definitions applying equation (15) (Table 3). We can see from Table 3 that the two different age-class structures result in different intensities of management. However, for the strictest BAWS definition the intensity of management is 100%, since the whole age class 11 is cut.

Table 3. Intensity of management

	Scenario	
BAWS (q)	1	2
1	9.2%	15.2%
2	10.2%	16.8%
3	11.3%	17.8%
4	12.7%	18.8%
5	14.5%	20 %
6	16.9%	21.8%
7	20.2%	24.3%
8	25.2%	28.3%
9	33.5%	35.4%
10	50.1%	50.7%
11	100 %	100 %

The actual harvest levels during the transition period's second half (2016 – 2020) for scenarios 1 and 2 were 21.3 mill m^3 and 54.4 mill m^3 respectively. Figure 4 shows the computation option A's output for 2016 – 2020 compared to the actual harvest level of 2016 – 2020. Computation option A's output is different than the actual forest development we simulated to describe the transition period. Compared to the transition period computation option A overestimates the area under old age classes at the beginning of the compliance period and produces low harvest levels for 2016 – 2020.

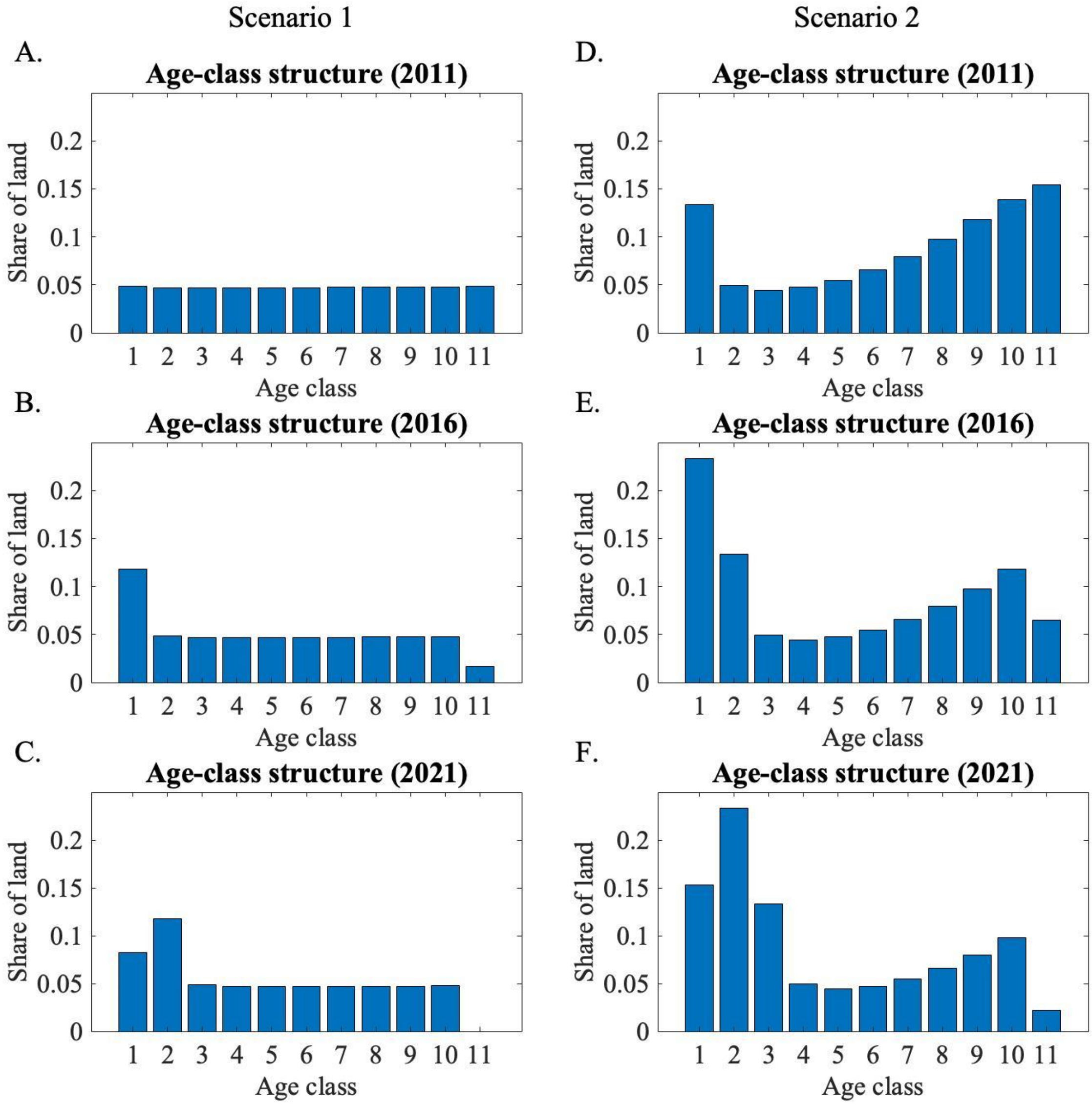

Figure 3. Scenario 1 and 2 forest age-class structure development. Each forest state is described at the beginning of the year.

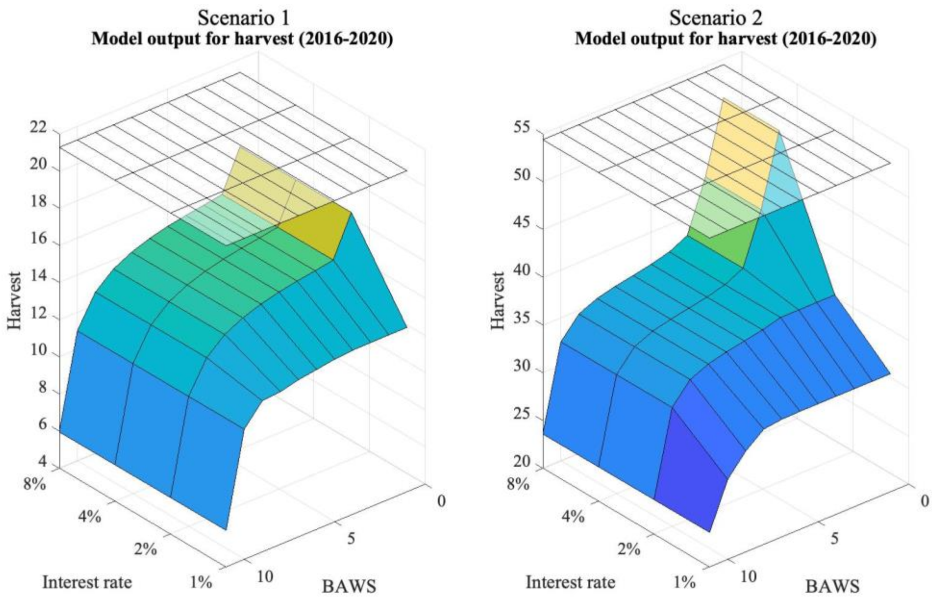

Figure 4. Model outputs for harvest (2016 – 2020) (colored surface) in computation option A compared to the actual harvest level (black lined mesh surface).

The FRLs were computed for options A and B applying the parameters for intensity of management from Table 3. In Table 4, we can observe the differences in objective function values with different interest rates and BAWS definitions. From the results we can see that a looser BAWS definition (i.e. more age classes are consider to be available for wood supply), for most cases, gives a higher or equal value for the objective function, which would give an incentive to apply looser BAWS definition. The biggest difference is between the BAWS 10 and 11. One exception in the results can be observed for BAWS 1 and 2 in scenario 1 with interest rates of 1 and 2 %, when computation option B is applied. In this case the tighter BAWS gives higher value for the objective function. Most likely, this is due to the age-class structure at the starting year. From Figure 3, we can observe that there was a large share of land allocated to age class 2 at the end of the transition period. The difference in the objective function's value, however, is insignificantly small. If the interest rate is 4 or 8 %, the looser BAWS definition will always result in a higher or equal value for the objective function.

Table 4. Objective function values for different interest rates and BAWS definitions

Scenario 1					Scenario 2				
Computation option A.					Computation option A.				
		Interest rate					Interest rate		
BAWS	1 %	2 %	4 %	8 %	BAWS	1 %	2 %	4 %	8 %
1	703,77	338,18	160,35	74,09	1	1095,66	535,73	265,37	135,44
2	703,77	338,10	159,65	72,91	2	1095,66	535,73	264,89	133,34
3	703,77	337,94	158,89	71,94	3	1095,66	535,73	263,76	129,90
4	703,76	337,69	158,17	71,18	4	1095,66	535,73	262,55	126,79
5	703,75	337,31	157,45	70,53	5	1095,66	535,66	261,08	124,13
6	703,73	336,88	156,76	69,93	6	1095,61	535,23	258,94	121,79
7	703,70	336,48	156,10	69,35	7	1095,43	533,75	256,31	119,89
8	703,68	336,11	155,45	68,72	8	1094,94	531,29	253,58	118,45
9	703,66	335,73	154,74	67,92	9	1093,05	528,48	251,35	117,45
10	703,52	335,18	153,79	66,73	10	1089,67	525,13	249,49	116,58
11	702,01	333,33	151,43	63,96	11	1085,54	520,61	246,88	114,36
Scenario 1					Scenario 2				
Computation option B.					Computation option B.				
		Interest rate					Interest rate		
BAWS	1 %	2 %	4 %	8 %	BAWS	1 %	2 %	4 %	8 %
1	709,21	336,68	157,12	72,02	1	1062,95	507,64	241,63	118,90
2	709,21	336,69	157,01	71,68	2	1062,95	507,64	241,63	118,64
3	709,20	336,61	156,32	70,31	3	1062,95	507,64	241,48	116,57
4	709,19	336,46	155,47	69,10	4	1062,95	507,64	240,53	113,03
5	709,18	336,16	154,57	68,04	5	1062,95	507,57	238,98	109,63
6	709,12	335,72	153,60	67,06	6	1062,95	507,19	236,44	106,31
7	708,99	335,18	152,59	66,08	7	1062,95	505,85	233,43	103,47
8	708,78	334,57	151,53	65,01	8	1062,24	502,81	229,69	100,96
9	708,47	333,77	150,29	63,66	9	1059,93	499,14	226,27	98,83
10	707,81	332,43	148,48	61,58	10	1055,59	494,56	222,95	96,55
11	699,34	323,69	139,46	52,95	11	1047,99	486,67	216,38	90,51

Figure 5 presents the projected FRL harvest levels for both scenarios and computation options. There is a big difference in the harvest levels between the computation options A and B. The harvest levels are higher if computation option A is applied. With a higher interest rate the harvests are higher or equal than with the lower interest rate for both computation options. If the intensity of management restriction is binding, the interest rate has no effect on the results. This means that it is optimal to cut the whole intensity defined share of the mature stands. The most extreme result is for the BAWS 11 in the scenario 1, when computation option B is applied. In this case the oldest 11th age class is completely cut down before the compliance period. Thus, the harvest level in the FRL is zero.

The effect of the BAWS definition on the FRL harvest levels is more complex (Figure 5). With computation option B, the looser BAWS definition always results greater harvest levels for the FRL. If the computation option A is applied, the stricter BAWS can result in a higher harvest level as well. The reason for this is the fact that computation option A overestimates the area under area under older age classes at the beginning of the compliance period. Overestimation of mature stands is most notable with BAWS 11. Since the intensity of management for BAWS 11 is 100%, it is possible to cut the whole 11th age class in the FRL. In computation option A, when looser BAWS definitions are used, the harvest levels are more stable between 2016 – 2020 period (Figure 4) and FRL (Figure 5). Thus, there is no similar peak in the FRL harvest level as with the BAWS 11.

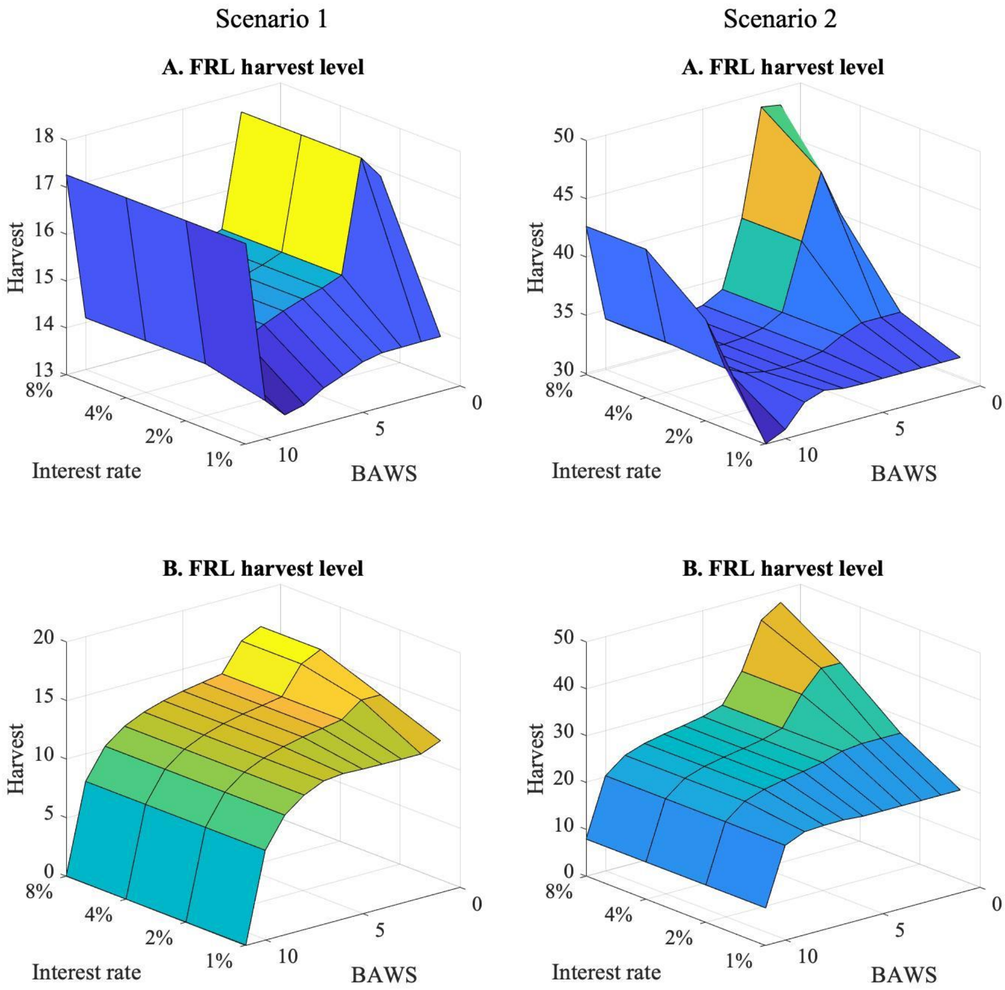

Figure 5. FRL harvest for computation options A and B with different interest rates and BAWS definitions

Figure 6 shows the results in terms of physical forest net carbon sink in the FRL. The results follow the same pattern as with the harvest levels. The carbon sink is greater (emissions are lower) with computation option B. Higher interest rate results in smaller or equal carbon sink (greater or equal emissions). With computation option A, the BAWS definition affects the results as with the harvest levels. Since option A overestimates the harvest level for FRL, the FRL carbon sink is smaller. For computation option B the stricter BAWS definition always results greater carbon sink. In monetary terms the net present value of per period carbon sink is lower when the harvests are higher in the FRL.

All of the three examined computation assumptions had an effect on the results, when harvest levels have increased and the rotation lengths have decreased after the reference period. If a member state aims to maximize its harvesting possibilities, it has an incentive to apply a specific set of computation choices. The early starting year for the computation tends to overestimate the area under older age classes and results in higher FRL harvest levels. A high interest rate tends to result in higher harvest levels if the intensity of management restriction is not binding. The BAWS definition has an impact on the FRL, and the effect is partly dependent on the starting year of the computation.

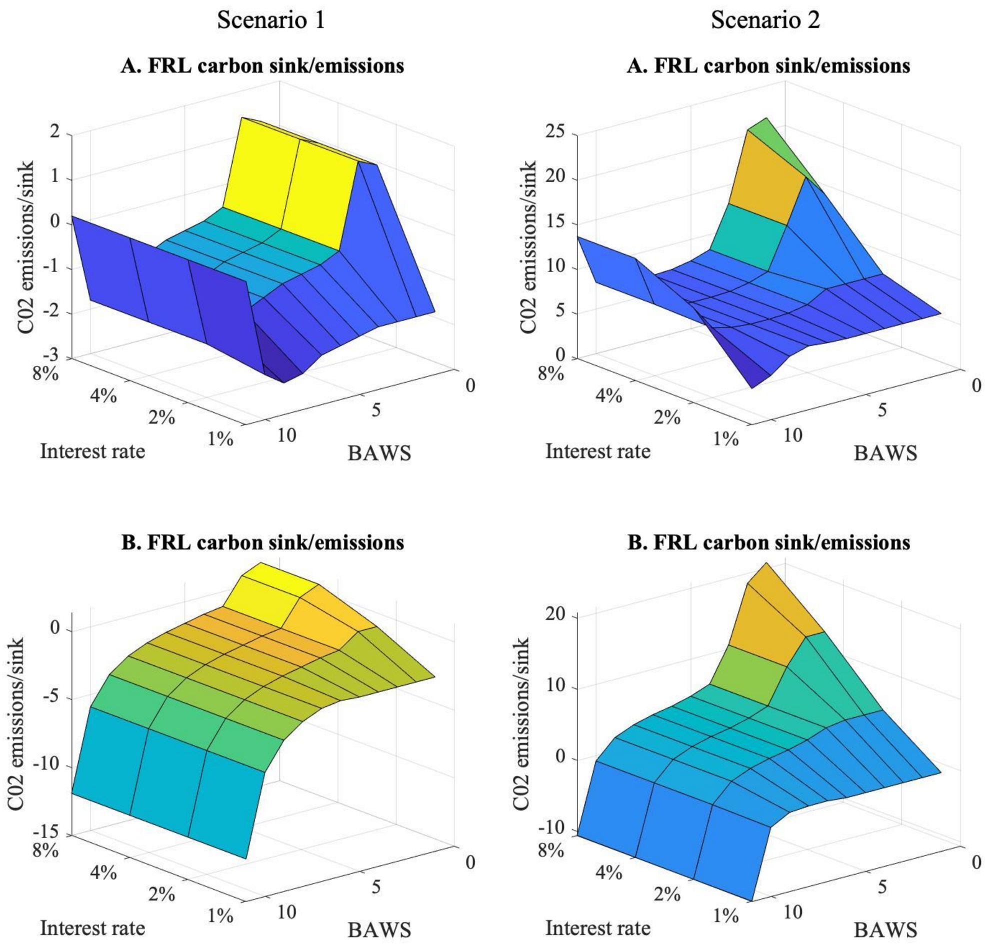

Figure 6. FRL carbon sink/emissions for computation options A and B with different interest rates and BAWS definitions

7 Discussion

The European Union’s LULUCF regulation (EU) 2018/841 aims to avoid the problems of the Kyoto Protocol’s second period, where the emissions from the managed forest land were accounted against an inaccurate reference level (Krug 2018). However, this objective may not be fulfilled. In Grassi et al. (2018), where they present their principle to calculate FRL, they show that an increase in the biomass available for wood supply increases the future harvest levels due to age-related dynamics. What seems to be left unnoted is the fact that the BAWS is very loosely defined. This is problematic since it can be one of the key definitions for the FRL projection. According to our results, choosing a looser definition for the BAWS mostly results in greater harvest levels for the member state’s FRL. Such results can be observed from the Finnish FRL proposal’s development. Despite the provided step-by-step guidance document by Forsell et al. (2018), the interpretations of the LULUCF regulation set requirements for the FRL projection can be different between the member states. At least Estonia, Belgium, Slovakia, Latvia, Lithuania, Norway (non-EU member), France, Spain and Poland have applied the intensity of management principle suggested by Grassi and Pilli (2017) and Grassi et al. (2018) for the FRL projection.

The forest reference level with the greatest carbon sink is in France. The size of the sink is -55 Mt CO_2. In France the size of the carbon sink is expected to increase, and the preliminary FRL carbon sink estimate for 2026 – 2030 is greater than the FRL proposal for 2021 – 2025. France’s FRL was projected by the dynamic MARGOT model. The model simulates growth, mortality and forest management at a strata scale for 5-year periods. The forest management practices of the reference period were defined as a rate of felled trees per diameter class. In their National Forestry Accounting Plan, they point out that they don’t have sufficient data from the whole reference period. Thus, the national forest inventory (NFI) data from 2005 – 2014 period was used to estimate the forest management of the reference period. For some regions, the harvest level exceeds the increment in the FRL projection. (NFAP France 2019.)

France also received requirements to revise their first FRL proposal from the European Commission (2019b). They were asked to demonstrate that the model is able to project the forest development that is based on the reference period’s forest management and how the model takes into account the forest age-class structure. The Commission also noted that there is a discrepancy between the model output and the GHG inventories concerning the biomass development for 2010 – 2016. The model output showed higher carbon sink than the GHG inventories (NFAP France 2018). France was required to provide data for the rotation lengths, increment and dynamic age-characteristics of the forests.

In Spain the forest reference level carbon sink is -33 Mt CO_2. They developed the Vael model to project the FRL as suggested in the guidance document by Forsell et al. (2018) (NFAP Spain 2019). They use the forest management practices of the reference period for the whole projection from 2010 onwards. The Vael model output is based on the region, forest type and management practices. The historical forest management practices are defined from the NFI data by the national forestry experts. The forest management practices are defined per maturity class by regime, share of biomass harvested, number of transition years between classes and the timing of the management activities (i.e. thinning or clearcut). The data that describes the state of the forest is from the NFI results. However, for some regions the latest data is more recent than for the others (oldest 2002, latest 2017). (NFAP Spain 2019.)

Spain had several issues concerning the used model and data in their first FRL proposal. The European Commission (2019b) required Spain to provide a proper description of the model and show that it is capable to project the historical management practices of the reference period. The Spanish FRL output has discrepancies with the GHG inventories. The data provided with the Spanish FRL was not sufficient to prove its creditability. A more accurate description of the model and forest in different development classes was required. The produced harvest level increases during the commitment period and the Vael model output is not consistent with the historical harvest levels. In the second FRL proposal of Spain (NFAP Spain 2019) the projected harvest levels are higher than statistical level for the years 2010 – 2013 and lower for the years 2014 – 2018. It remains unclear whether the Vael model results in an overestimated number of mature stands that leads to an overestimated harvest level for the compliance period.

The forest land in Estonia has experienced a land reform where public forest land has been privatized. Most of the privatization has been carried out before the compliance period. During the reference period the majority of these forests were still not under forest management and were considered as "*forest not available for wood supply*". At the starting year of the FRL projection (year 2017) there were significantly more forests that were considered available for wood supply compared to the reference period. (Estonian Ministry of Environment 2019.) The European Commission (2019b) asked Estonia to explain whether the historical forest management practices are applicable to the forest land that was under privatization.

The Swedish NFAP (Government Offices Sweden 2020) has used a model called Heureka RegVis to project the forest reference level. Sweden's reference level sink is -39 Mt CO_2. They have determined the harvest intensity as a ratio between harvests and increment. This harvest to increment ratio was 77% for managed forest land. This approach is different than the management of intensity approach. The European Commission (2019b) required several corrections from Sweden based on the first FRL proposal. The historical forest management practices were not described transparently. Sweden was required to explain how the used modelling approach takes the age-class structure into account, when the harvest level is determined by the increment. More information on the rotation lengths, age-related dynamics and increment were required.

The development of the Finnish FRL suggests that it aims to report high harvest levels for the forest reference level. High interest rate, loose BAWS definition and early starting year of the projection overestimate the harvest level. During the process Finland has revised the FRL on European Commission's request, and the BAWS limits are now stricter in the second FRL proposal. This change decreased the computed harvest level. Assumptions concerning the BAWS definition and the applied interest rate, have been discussed in the public debate. Tahvonen (2018) argued that the applied interest rate is not justified to describe the reference period's forest management. Tahvonen (2019) criticized that the applied maturity limits are not valid for the whole reference period. Soimakallio (2019), pointed out a controversy with the definition for the mature forest stands. The National Forest Inventory (NFI) defines mature forests by diameter and the FRL defined mature stands by age. As a result, the used MELA model overestimated the harvest level compared to the inventory data. The Natural Resource Institute Finland admitted this error in the FRL and revised the definition. However, the MELA output for the years 2016 – 2018 still shows more mature forests stands than can be observed from the latest NFI data. From our results we can see that this can happen, if a member state applies early starting year for the FRL projection.

The question on the starting year of the projection seems to be more important than was concluded in the assessment by Forsell et al. (2019). They used two alternative starting years 2010 and 2015. According to their results the starting year has only a small effect on the FRL. However, we argue that this might have severe impacts if the member state has experienced considerable increase in harvest levels after the reference period. The LULUCF regulation states that the FRL should be in line with the historical GHG inventory data (EU 2018/841). However, e.g. in Finland, the projection starts from 2016 and the years before the compliance period are not in line with the actual forest state.

The MELA model overestimates the number of mature stands. From this it can be concluded that the model projection cannot be in line with GHG inventories either. Thus, the modelled forest state at the beginning of the compliance period is not in line with the reality. It is important that the European Commission continues to require transparent documentation of the modelled forest development from the member states.

The guidance document by Forsell et al. (2018) and the regulation itself asks for a robust and accurate documentation of the historical forest management practices. In the case of Finland, there are multiple different forest management guidelines and regulations from the reference period. It seems that it is preferable to choose management practices that are the least restrictive for maintaining high harvest levels. For the first FRL proposal Finland used silvicultural recommendations proposed by Tapio (2006). The second FRL proposal included Forest Act (1997), because some of the management practices of Tapio (2006) would have been illegal in the beginning of the RP. However, the FRL still neglects the Tapio (2001) silvicultural recommendations, which suggested even stricter management than the Forest Act (1997). Looking at the age structure of the Finnish forests, it seems that applying looser maturity limits (i.e. BAWS definition) adds a lot of area to the development class of the mature stands. Perhaps a more justified principle would be to apply average forest management as was suggested in the guidance document by Forsell et al. (2018).

In this study we have focused on the forest carbon sequestration. However, the LULUCF regulation requires also that the FRL considers biodiversity issues. This requirement is not unambiguously included in the suggested principles. As can be seen from our results, the intensity of management can lead to a situation where harvests exceed the increment, same conclusion was made by Nabuurs et al (2018). Thus, using historical intensity is not a sufficient restriction on its own to secure biodiversity. In analysis by Nabuurs et al. (2018) harvests were restricted to 90% of the increment but yet harvests were still estimated to increase during the compliance period. For example, France admits that in some of its regions the intensity of management can be more than 100% (NFAP France 2019). In the Finnish FRL sustainability is covered by the assumption that the harvest levels cannot decrease between 2016 and 2060. The negative effects of increasing harvest rates have been discussed in Finland. In 2017, 68 scientists from different fields signed a declaration that questioned the ability of the Finnish policy making to safeguard biodiversity and climate change mitigation while increasing harvest rates (BIOS 2017).

For the Kyoto protocol's forest reference levels, it was shown that the countries are incentivized to report as high harvest levels as possible (Frieden et al 2012). This incentive is still present with the new LULUCF regulation. If the European Union aims to have well planned pathway towards its climate targets, the role of forest carbon sink should be taken seriously. Further actions should be developed, to secure and preserve the carbon sinks of the European forests. The European Commission (2019b) has made several FRL revision requests for the member states. Almost all member states had issues that needed clarification or revision. The final FRLs are yet to be announced and the Commission is currently evaluating whether the member states have been able to revise their results as requested.

The LULUCF regulation aims to incentivize the member states to preserve and enhance the forest carbon sinks. However, the private forest owners are not incentivized by the LULUCF regulation itself. Nonindustrial private forest owners' decisions are influenced by many market and nonmarket benefits (Kuuluvainen et al. 1996). There are some empirical examples of forest carbon sequestration policies outside the EU that take the private forest owners into account. The California Cap-and-Trade system features a voluntary Forest Offset Protocol, where the forest owners are paid for additional forest carbon sequestration (Anderson et al. 2017). In the New Zealand Emissions Trading Scheme forests are included in the system and forest owners can produce tradable emission units (NZUs) but are obligated to compensate the emissions from harvesting (Carver et al. 2017). It might be necessary to create member state specific mechanisms to incentivize forest owners to comply with the LULUCF regulation.

In environmental economics it is common practice to include externalities in the decision-making process through market intervention (Phaneuf and Requate 2017). The forest carbon sinks should be considered as a positive externality due to their have climate change mitigating abilities. Global scientific community suggests that the forest carbon sinks should be used in the fight against climate change (IPCC 2018, EASAC 2018). Forests sequester carbon as they grow, even without any active carbon policies. Thus, there exists a certain level of carbon sink that can be obtained without creating incentives for the forest owners. According to Tahvonen and Rautiainen (2017) subsidizing all carbon sequestration is an unnecessary social cost burden. Thus, a baseline for forest carbon sinks is needed to define what level of carbon sequestration is additional, i.e. result of a carbon sink enhancement. The forest reference levels could be seen as an effort towards setting such a baseline but for now the LULUCF regulation leaves too much room for the member states to affect the FRL results through computation choices. The member states can hold information on the historical forest management from the European Commission to ensure higher harvest levels during the compliance period. The European Commission examines and approves the national FRL proposals but might not have all the necessary information to do so. Thus, under asymmetric information the LULUCF regulation and the forest reference levels are not able to ensure the additionality of the carbon credits.

8 Conclusions

This thesis provides an analysis of the forest reference level projection compared to the Kyoto Protocol by examining the effects of the FRL computation choices. These computation choices do not violate the provided guidance document by Forsell et al. (2018) and are used in the national forest reference level projections. Using the market-level partial equilibrium age-class model for forestry and agriculture we conducted a numerical analysis on the FRL computation in a case where member state has experienced harvest-increasing policy change after the reference period.

In our results, we showed that the choices on the biomass available for wood supply, starting year of the projection and the interest rate leave room to overestimate (underestimate) the harvest level (carbon sink) in the forest reference level. Thus, the Paris Agreement's requirement for science-based actions (UNFCCC 2015) is not fulfilled in the EU framework because of the problems in the LULUCF regulation. This is the outcome of our numerical analysis. Other existing research also indicates that the FRL computation is affected by the computation choices. The European Union still has issues in including forests in its climate policy and in avoiding the problems of the Kyoto Protocol. The LULUCF policy clearly needs further development to be able to incentivize additional forest carbon sequestration.

In Finland the FRL seems to be projected in a way that the future harvest possibilities are restricted as little as possible. The results have changed, after the European Commissions required revision for the FRL. In the second proposal the BAWS was defined to be stricter, and the projected harvest level decreased. The Finnish FRL projection still neglects the silvicultural recommendations that were used 2001 – 2005. Using those would most likely reduce the harvest level even more. The chosen interest rate, loose BAWS definition and the starting year of the projection seem to have caused overestimation in the projected FRL harvests. It remains to be seen if the Finnish forest reference level proposal is accepted by the European Commission.

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Appendices

Appendix 1. AMPL/Knitro code for forest reference level projection

Model file

```
param T; #number of periods
param n; #number of age-classes
param r;#intrest rate
param b=(1/(1+r));#discount factor
param f {s in 1..n};#biomass
param alpha;
param gamma;
param W;
param U;
param x0 {s in 1..n};
param intensity;
param w;#regeneration cost
param k;#carbon release
param o;#SCC
param h;#period length
param d;#carbon per m3
var x {s in 1..n, t in 0..T+1}>=0; #share of land in forest age-class
var y {t in 0..T-1}>=0; #share of agriculture land
var c {t in 0..T-1}>=0; #harvest
var z {t in 0..T-1}>=0; #harvested area
var a1 {t in 0..T-1}>=0; #BAWS 1
var a2 {t in 0..T-1}>=0; # BAWS 2
var a3 {t in 0..T-1}>=0; # BAWS 3
var a4 {t in 0..T-1}>=0; # BAWS 4
var a5 {t in 0..T-1}>=0; # BAWS 5
var a6 {t in 0..T-1}>=0; # BAWS 6
var a7 {t in 0..T-1}>=0; # BAWS 7
var a8 {t in 0..T-1}>=0; # BAWS 8
var a9 {t in 0..T-1}>=0; # BAWS 9
var a10 {t in 0..T-1}>=0; # BAWS 10
var a11 {t in 0..T-1}>=0; # BAWS 11
var woodprice {t in 0..T-2}=U*alpha*(c[t])^(alpha-1);
var aglandprice {t in 0..T-2}=b*W*gamma*y[t]^(gamma-1)/(1-b);
var carbon {t in 0..T-2}=b^((t+1)*h)*(o*(sum{s in 1..n} (f[s]*(x[s,t+1]-x[s,t]))+(k-1)*c[t]));#value of carbon sink
var carbonsink {t in 0..T-2}=(-1)*d*sum{s in 1..n} (f[s]*(x[s,t+1]-x[s,t]));#physical carbon sink
var biomass {t in 0..T}=sum{s in 1..n} (f[s]*x[s,t]);
var intensity1 {t in 0..T-2}=(z[t]/a1[t]);#intensity
var intensity2 {t in 0..T-2}=(z[t]/a2[t]);#intensity
var intensity3 {t in 0..T-2}=(z[t]/a3[t]);#intensity
var intensity4 {t in 0..T-2}=(z[t]/a4[t]);#intensity
var intensity5 {t in 0..T-2}=(z[t]/a5[t]);#intensity
var intensity6 {t in 0..T-2}=(z[t]/a6[t]);#intensity
var intensity7 {t in 0..T-2}=(z[t]/a7[t]);#intensity
var intensity8 {t in 0..T-2}=(z[t]/a8[t]);#intensity
var intensity9 {t in 0..T-2}=(z[t]/a9[t]);#intensity
var intensity10 {t in 0..T-2}=(z[t]/a10[t]);#intensity
var intensity11 {t in 0..T-2}=(z[t]/a11[t]);#intensity
maximize objective_function: sum{t in 0..T-2} b^((t+1)*h)*(U*c[t]^alpha+W*(y[t])^gamma-x[1,t+1]*w);
subject to const1{s in 1..n-2, t in 0..T-1}: x[s+1,t+1]-x[s,t]<=0;
subject to const2{t in 0..T-1}: x[n,t+1]-x[n,t]-x[n-1,t]<=0;
subject to const3{t in 0..T-1}: y[t]=1-sum{s in 1..n} x[s,t];
subject to const4{s in 1..n}: x[s,0]=x0[s];
subject to const5{t in 0..T-1}: c[t]=sum{s in 9..n-2} (f[s]*(x[s,t]-x[s+1,t+1]))+f[n]*(x[n,t]+x[n-1,t]-x[n,t+1]);
```

```
subject to const6{t in 0..T-1}: z[t]=sum{s in 1..n-2} (x[s,t]-x[s+1,t+1])+(x[n,t]+x[n-1,t]-x[n,t+1]);
subject to const7{t in 0..T-1}: (z[t]/a9[t])<=intensity;
subject to const8{t in 0..T-1}: a1[t]=sum{s in 1..n-2} (x[s,t])+x[n,t]+x[n-1,t];#biomass available for wood supply
subject to const9{t in 0..T-1}: a2[t]=sum{s in 2..n-2} (x[s,t])+x[n,t]+x[n-1,t];#biomass available for wood supply
subject to const10{t in 0..T-1}: a3[t]=sum{s in 3..n-2} (x[s,t])+x[n,t]+x[n-1,t];#biomass available for wood supply
subject to const11{t in 0..T-1}: a4[t]=sum{s in 4..n-2} (x[s,t])+x[n,t]+x[n-1,t];#biomass available for wood supply
subject to const12{t in 0..T-1}: a5[t]=sum{s in 5..n-2} (x[s,t])+x[n,t]+x[n-1,t];#biomass available for wood supply
subject to const13{t in 0..T-1}: a6[t]=sum{s in 6..n-2} (x[s,t])+x[n,t]+x[n-1,t];#biomass available for wood supply
subject to const14{t in 0..T-1}: a7[t]=sum{s in 7..n-2} (x[s,t])+x[n,t]+x[n-1,t];#biomass available for wood supply
subject to const15{t in 0..T-1}: a8[t]=sum{s in 8..n-2} (x[s,t])+x[n,t]+x[n-1,t];#biomass available for wood supply
subject to const16{t in 0..T-1}: a9[t]=sum{s in 9..n-2} (x[s,t])+x[n,t]+x[n-1,t];#biomass available for wood supply
subject to const17{t in 0..T-1}: a10[t]=sum{s in 10..n-2} (x[s,t])+x[n,t]+x[n-1,t];#biomass available for wood supply
subject to const18{t in 0..T-1}: a11[t]=sum{s in 11..n-2} (x[s,t])+x[n,t]+x[n-1,t];#biomass available for wood supply
subject to const42{t in 0..T-2}: sum{s in 1..n} (x[s,t])=sum{s in 1..n} (x[s,t+1]);
```

Data file

```
param T:=200;#periods
param r:=0.01; #0.02 #0.04 #0.08
param n:=24;#number of age classes
param W:=2;
param U:=5;
param alpha:=0.7;
param gamma:=0.2;
param h:=5; #period length
param d:=0.7;
param w:= 60; #10 #regeneration cost
param k:= 1;
param o:= 0.2; #social cost of carbon
#Intensity of management for scenario 1
#param intensity:=0.0924206     ;
#param intensity:=0.101886      ;
#param intensity:=0.113054      ;
#param intensity:=0.126967      ;
#param intensity:=0.144802      ;
#param intensity:=0.168529      ;
#param intensity:=0.201715      ;
#param intensity:=0.251634      ;
#param intensity:=0.33479       ;
#param intensity:=0.501064      ;
#param intensity:=0.999792      ;
#Intensity of management for scenario 2
#param intensity:=0.1520615     ;
#param intensity:=0.1682295     ;
#param intensity:=0.1776055     ;
#param intensity:=0.1877435     ;
#param intensity:=0.200438      ;
#param intensity:=0.217732      ;
#param intensity:=0.24305       ;
#param intensity:=0.2832195     ;
#param intensity:=0.354478      ;
#param intensity:=0.5069045     ;
#param intensity:=0.9995905     ;

#Growth parameter
param f:=
   1 0
   2 0
   3 0
```

```
    4 7
    5 30
    6 76
    7 139
    8 206
    9 269
    10 321
    11 362
    12 393
    13 415
    14 431
    15 442
    16 449
    17 455
    18 458
    19 461
    20 462
    21 463
    22 464
    23 465
    24 465;
#Scenario 1 2016 forest state
param x0:=
1           0.117781
2           0.048382
3           0.0466696
4           0.0466522
5           0.0466909
6           0.0467982
7           0.0469869
8           0.0473361
9           0.0475105
10          0.0477082
11          0.016447
#Scenario 1 2021 forest state
#param x0:=
1           0.0822751
2           0.117781
3           0.048382
4           0.0466696
5           0.0466522
6           0.0466909
7           0.0467982
8           0.0469869
9           0.0473361
10          0.0475105
11          0.000001
#Scenario 2 2016 forest state
#param x0:=
1           0.2335
2           0.133606
3           0.0491897
4           0.0441678
5           0.0473934
6           0.0547406
7           0.0655494
8           0.0797994
9           0.097432
10          0.117795
11          0.0651731
```

```
;
#Scenario 2 2021 forest state
#param x0:=
1		0.153166
2		0.2335
3		0.133606
4		0.0491897
5		0.0441678
6		0.0473934
7		0.0547406
8		0.0655494
9		0.0797994
10		0.097432
11		0.0218819;
```

Run file

```
option knitro_options "maxit=6000 opttol=1.0e-9 xtol=1.0e-9 ftol=1.0e-9";

solve;
option display_width 2;
option display_width 1000;
display x, y, c, z, objective_function, woodprice, aglandprice, carbon, carbonsink, biomass,
intensity1, intensity2, intensity3, intensity4, intensity5,
intensity6, intensity7, intensity8, intensity9, intensity10,
intensity11;
```